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An empirical approach to determining speed limit credibility

Abstract

There is now a body of literature on speed limit credibility, particularly in connection with speed management under the overall umbrella of “Safe Systems”. However, there is rather little empirical work on the underlying factors that determine the credibility of speed limits and on how to enhance credibility for a given type of road. The study reported here aimed to investigate how factors such as road layout and the roadside environment together with drivers’ perception of risk affect speed limit credibility. It also aimed to provide a measurement of speed limit credibility and how to set more credible speed limits to improve drivers’ speed compliance. A picture questionnaire and a driving simulator in an automated condition in a simulator were adopted to obtain the measurements. The results suggest that certain road layout and environment features influence speed limit credibility. The research results show that five new indicators can be used as a reference for deciding on a credible speed limit in a given road environment: the most common choice of speed limit by drivers; the highest credible rating score value; indication of comfort with speed in automated driving; risk rating in the range from feeling safe to very safe; arousal indicated by skin conductance. Applying these indicators makes it possible to determine a limit that is credible for most motorists in a given road environment. Improving the credibility of a speed limit will lead to better speed management overall.

Keywords

Credible; speed limit; road layout; risk perception

1 Introduction

Speeding is an important risk factor in road traffic injuries. It influences both road crash risk and the severity of the injuries caused by crashes and is more significant than almost all other known risk factors (WHO, 2008; Elvik et al., 2009; OECD, 2018). Curtailing high speeds can prevent the occurrence of crashes, reduce their overall impact, and lessen the severity of injuries sustained by the victims when crashes do occur (WHO, 2008). A relatively safe speed which brings lower fatality rate would be 30km/h for situations where there can be conflicts between pedestrians and vehicles collision, 50km/h for side impacts at junctions and 70km/h for head-on crashes (Richards, 2010). Current UK speed management does not meet the requirement to lower the speed limit to a safer level even at the expense of the mobility function. The impact speed and risk of fatality relationship could be used to derive rules with which to set a safer speed limit to minimize crash numbers and crash severity if the accident does occur (KiwiRAP, 2010).

Speed management can be defined as a set of measures to limit the negative effects of excessive or inappropriate speed (exceeding speed limits or not matching the driving conditions) in the transport system (OECD, 2006). There are a range of measures to address speed management, including enforcement, engineering, education and publicity, depending on the prevailing circumstances. To achieve wider public acceptance of enforcement, credible speed limits need to be set. Therefore, there should be a focus on setting credible speed limits to improve effective speed management.

Although various items of research literature have focused on different road factors affecting speed limit credibility (Aarts et al., 2009b; Aarts et al., 2009a; SWOV, 2012b; ETSC, 2010; van Nes et al., 2008; van Nes et al., 2007; Goldenbeld and van Schagen, 2007), there is no evidence to measure credibility level. Therefore, this study aimed to set a more credible speed limit by manipulating road layout and the roadside environment. In order to measure speed limit credibility, it is necessary to investigate how road layout and the roadside environment affect speed limit credibility and to investigate various measurements of "credible speed limits" based on the experimental evidence.

2 Literature review

2.1 Previous research on speed limit credibility

In terms of the definition of speed limit credibility, SWOV (2012a) reports that a credible speed limit is a limit that matches the image which is evoked by the road and the traffic situation. Goldenbeld and van Schagen (2007) claim that certain specific road and environment combination features influence the credibility of the speed limit. They defined credibility as the speed limit that drivers consider logical or appropriate in light of the characteristics of the road and its immediate surroundings through specific consistency and continuity of road design.

Credibility research has only been taken up by a small number of Dutch researchers in the recent decade. Thus van Nes et al. (2007) listed five road and road environment characteristics which have been identified as influencing the credibility of speed limits. Road layout features were found to influence credibility on 80km/h rural roads in the Netherlands (Goldenbeld and van Schagen, 2007). Aarts et al. (2009a) found that five road layout factors influenced speed behaviour and credibility. They also discussed how, for a given speed limit, features of the road layout and the roadside environment can encourage higher or lower speeds, which they termed 'accelerators' and 'decelerators'. Accelerators are elements of the road or environment that intuitively encourage a higher speed, while decelerators encourage a lower speed. For example, a wide road as an accelerator encourages drivers to drive at a higher speed while a narrow road as a decelerator encourages drivers to drive at a lower speed (SWOV, 2012b). For other factors, long tangents, a physical speed limit sign not being present, open, clear road environment and smooth road surface have been justified as further accelerators (SWOV, 2012b). Currently, no standard tools are available to measure speed limit credibility because credibility is internal to those who drive in a given situation, which is difficult to capture. In addition, the concept has only been based on a theoretical view and has not been made concrete and applicable from a practical view. Therefore, a holistic measurement of speed limit credibility needs to be established.

2.2 Previous research on risk perception

An important human factor considered in the evaluation of road users' behaviour is their risk perception as regards road safety. According to Sjoberg (1998), perceived consequences of a negative event should be applied as a measure of risk perception, such as estimating the influence of perceived risk on risky driving behaviour. The emotional response can be measured by at least two different methods — affective reports and physiological reactivity (Lang, 1969, cited in Bradley and Lang, 1994). Accordingly, in this research, the risk perception information was acquired by the following two methods:

1) Subjective self-assessment — the individual participant reports the level of risk feeling via a self-assessment questionnaire.

2) Objective electrodermal activity measurement — an entity (human or machine) observes the monitored individual and uses for defining autonomic changes in the electrical properties of the skin.

2.2.1 Subjective risk perception

It can be inferred that subjective risk perception comes from the road environment (road layout and design), driving speed, oncoming vehicles, the conflict between vehicle and cyclists and running off the road etc. Subjective perceived risk also depends on driver capability which is determined by the upper level of driver competence (Fuller et al., 2008). Other human factors such as fatigue, distraction and motivation affect driver capability then subjective risk perception. Subjective risk perception is therefore an individual's assessment of the risk of a situation which is also based on their knowledge about objective risk. To understand how drivers' subjective risk perception of a road situation relates to their perception of the credible speed limit, we developed measurements of cognitive-based risk perception and emotion-based risk perception, as identified by Rundmo and Iversen (2004), to create a scale to measure drivers' perception of risk or hazard to themselves on the road. "Cognition-based" refers to a belief-based component of risk perception to evaluate the probability of an accident. "Emotion-based" refers to thinking of or being exposed to the risk source or risky activity, e.g. the extent to which the respondent feels safe or unsafe. The higher the negative risk perception, the greater the likelihood of behaving differently.

2.2.2 Objective risk perception

The concept of objective risk is used to define a measurable level of road safety dependent on the numerical accident exposure value (Łukasik and Szymanek, 2012), which is linked to negative consequences, i.e. damages, injuries, sickness, losses and human suffering. Risky activities or hazards may be associated with fear, insecurity, worry and anxiety. To be specific, fear arises from appraisals of profound uncertainty as well as appraisals of situational control (Smith and Ellsworth, 1985). In this study, likewise, risk feeling can be generated when the given driving speed in an automated condition on the road is too fast compared with one's own comfort and desired driving speed.

Taylor (1964), Healey and Picard (2005), Ayzenberg and Picard (2014) and Nisa'Minhad et al. (2016) carried out research on drivers' galvanic skin response (a change in the electrical properties of the skin, also known as Electrodermal Activity) and the risk of an accident. Based on the findings, it can be predicted that physiological arousal for subjects will be lower in low risk situations, and higher in high risk situations. Therefore, the objective risk perception was measured by physiological Electrodermal Activity (EDA). Individuals higher in risk perception should show especially strong skin conductance reactivity to emotional (especially aversive) stimuli (Norris et al., 2007).

2.3 Road and roadside environment

The main crash types on two-lane rural single carriageways concern three factors: head-on collisions, run-off road single vehicle accidents and collisions with vulnerable road users (Lee and Mannering, 2002; De Waard et al., 1995). In addition, junction collisions often result in side-impacts and the probability of injury accidents at junctions was found to be roughly proportional to the 5th power of the speed of main-road traffic (Taylor et al., 2002). It is to be expected that proper road design, according to design principles, could reduce considerably the number and severity of accidents compared with the existing situation. Providing a hard shoulder is an effective way for directing drivers toward the centre of the lane and accident rates decrease with increases in shoulder width (Rosey et al., 2008; Rosey et al., 2009). Providing a cycle lane is an encouragement facility for existing cyclists and non-cyclists in determining route choice (Caulfield et al., 2012). Roundabouts with cycle tracks had the greatest reductions in injuries to cyclists and moped drivers compared to other crossings in the Netherlands (Schoon and van Minnen, 1994). The presence of a curve is a quite common road layout on rural roads. The radius of the curve also notably affects the speed choice (Montella et al., 2015a). Curve radius and steering competence both affect steering error during curve driving, resulting in compensatory speed choice (van Winsum and Godthelp, 1996). Horizontal curves on rural single carriageway have been recognized as a significant safety issue for many years. For the accident rate as the risk measurement, crash rates are 1.5 to 4 times higher on horizontal curves than on straight road sections, and 25-30% of all fatal accidents occur in curves (SafetyNet, 2009). Accident rate decreases as the radius increases (Wegman and Slop, 1998). As hard shoulders, cycle lane presence and curved roads are three significant components of road geometry when considered in the context of road safety, this experiment design considered the three factors' combination in the rural road environment.

The geometry of the road influenced drivers' road perception. For example, frequent intersections and driveways, the presence of horizontal curves, and pedestrians and sidewalks were justified to increased car drivers' perception of crash risk (Tarko, 2009). Although drivers compliance with the speed limit, they still perceive high risk on curved roads. Wide medians, wide paved roadways, and wide lateral clearance to obstructions reduced the perceived risk were justified to reduce the perceived risk (Tarko, 2009; Montella et al., 2015b). The vehicle stability and stopping sight distance also depend on the radius of the curve. These road geometry factors influence the perception of risk then the credibility of speed limit.

2.4 Aim and objectives

The study aimed to set a more credible speed limit in a given road and roadside environment to improve drivers' compliance with the speed limit.

The main objectives included:

- To investigate how the road layout and roadside environment affect the credibility of a speed limit
- To investigate various measurements of "credible speed limit" based on experimental evidence

3 Methodology

3.1 Overview

The methodological framework behind the research experiment is shown in Figure 1. Rural road environment was defined in terms of eight different road layouts. Risk perception was measured by both subjective risk perception and objective risk perception (EDA). Speed limit credibility was measured by both a picture questionnaire and subjective speed perception. Those indicators were implemented in two separated tasks: a questionnaire for Task 1 and a driving simulator study in an automated driving condition for Task 2. It was hypothesised that the layout of the rural road environment affected speed limit credibility and risk perception; also that risk perception affected speed limit credibility.

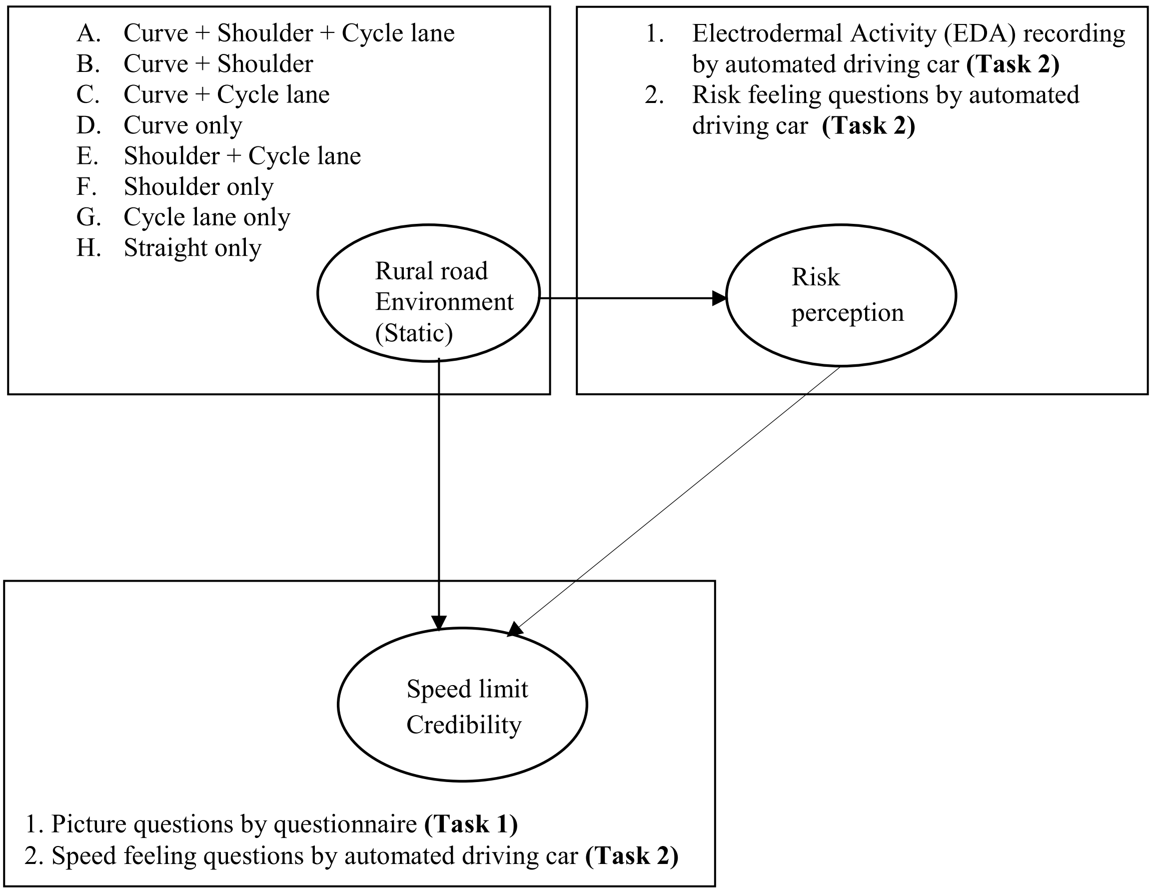

Figure 1 Experiment methodological framework

3.2 Participants

Because of the focus on drivers, the participants were required to have a valid driving licence, no matter what their driving experience was. The total participants were 17 males and 17 females, age ranging from 18 to 62 (M=31.71, SD=14.41), driving experience from 1 year to 45 years (M= 12.10, SD= 13.41). This research had ethical approval from the Research Ethics & Governance Committee of the University of Leeds.

3.3 Apparatus

For the questionnaire task, a 15”widescreen monitor was used to present a series of road scenes (Figure 2(a)). In total, eight screenshots of road scenes were presented. Each picture matched a few questions which are shown in Table 2. For each question, the participants placed a mark on a sliding scale which described their reaction to the picture. The participant had to answer the questions in a given time.

The automated driving task was conducted on a motion-base, high-fidelity driving simulator (University of Leeds Driving Simulator) (Figure 2 (b)). The simulator vehicle has an adapted vehicle cab of a 2005 Jaguar S-type model, housed in a 4m spherical projection dome with a 300° field of view projection system. The internal controls and dashboard instrumentation function as they would in a fully-operational vehicle. In automated driving mode, the driving simulator is controlled automatically with SAE Level 2 vehicle automation (hands off, feet off, conditional automation). The dynamic visual stimuli and motion stimuli consist of the road environment and automation speed.

The Biopac student lab system is an integrated set of software and hardware for life science data acquisition and analysis (Figure 2 (c)). Hardware includes the MP35 Acquisition Unit, electrodes, electrode lead cables, transducers, connection cables and other accessories. The physiological information is transferred via a cable to the Biopac Student Lab.

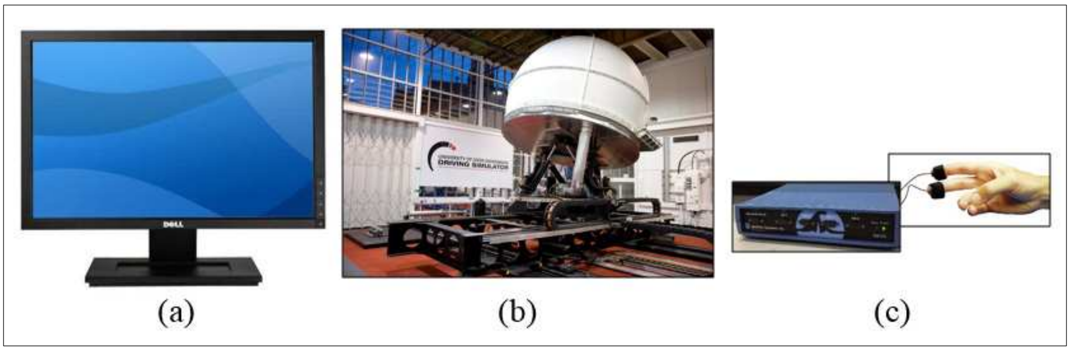

Figure 2 Experiment Apparatus

3.4 Experimental design

For the Task 1 questionnaire task, the experimental design was within-subjects, and each participant went through every road scenario (repeated measures). The experiment had three factors and each factor had two levels, a 2×2×2 factorial design. The eight road scenarios were modelled within the simulated scene with a lane width of 3.65 metres, the curve radius 200m, hard shoulder width of 1 metre and cycle lane width of 2 metres. Each rural single carriageway layout was modelled according to the UK Design Manual for Roads and Bridges (Volumes 6 and 8) (DMRB, 2002), with road markings, widths and signage, all conformed to current UK legislation. Table 1 below shows the 8 experimental conditions.

Table 1 Experimental road layout for task 1 and task 2

	Factors			Rural road layout combination
Experimental scenario number	**Road curve**	**Hard shoulder**	**Cycle lane**	
A	Present	Present	Present	Curve + Shoulder + Cycle lane
B	Present	Present	Absent	Curve + Shoulder
C	Present	Absent	Present	Curve + Cycle lane
D	Present	Absent	Absent	Curve only
E	Absent	Present	Present	Shoulder + Cycle lane
F	Absent	Present	Absent	Shoulder only
G	Absent	Absent	Present	Cycle lane only
H	Absent	Absent	Absent	Straight only

A__Curve + Shoulder + Cycle Lane

Figure 3 Rural single carriageway road scene example

For Task 2, the automated driving task, for the 8 rural road layout combinations, three levels of speed (40 mph, 50 mph and 60 mph) are used, a 2×2×2×3 factorial design with a total of 24 automated driving scenarios. A counterbalanced design is more likely to identify true differences in the effects of the various conditions. Counterbalancing the order of treatment is a control for sequential confounding. The treatments follow one another in an unpredictable fashion to minimise carryover effects (Barlow and Hayes, 1979).

3.5 Task procedure

3.5.1 Questionnaire (Task 1)

For Task 1, participants needed to remain seated in the office room, face the 15” monitor, and fill in a paper-based questionnaire. The participant was instructed that a series of pictures would be presented and several rating questions to each picture would be made using a paper-based questionnaire. The experimenter presented each rural road picture to the participant. The list of questions for the credibility questionnaire is given in Table 2. The questions included both a single choice and a sliding scale for each road scene. Credibility in this context meant reliable, trustworthy and appropriate, which was explained to participants before the task. For the sliding scale to judge whether a speed limit was credible or not based on a given road layout, a visual analogue scale (Vagias, 2006; Ohnhaus and Adler, 1975) was adopted. The visual analogue scale was a 100mm length bipolar sliding scale on which the subject could mark a point with a value from 0 to 100. A following demographic questionnaire probed participants for standard personal information, including gender, age and years of driving experience. A total of 8 screenshot pictures were presented to 34 participants in a balanced sequence to minimise carryover effects.

Table 2 Credibility Questionnaire survey (Task 1)

What is the lowest speed limit (mph) you think would be credible here?
20 30 40 50 60 70 80
How do you perceive a 70 mph speed limit on this type of road? Very non-credible-------------------------------------Very credible
How do you perceive a 60 mph speed limit on this type of road? Very non-credible-------------------------------------Very credible
How do you perceive a 50 mph speed limit on this type of road? Very non-credible-------------------------------------Very credible
How do you perceive a 40 mph speed limit on this type of road? Very non-credible-------------------------------------Very credible
How do you perceive a 30 mph speed limit on this type of road? Very non-credible-------------------------------------Very credible

3.5.2 Automated driving in the driving simulator (Task 2)

For Task 2 they were introduced to the driving simulator. They were escorted into the simulator and seated in the vehicle cab with the image generation system showing a 360-degree full white display. The escorting researcher verbally repeated the characteristics of the requisite driving scenario, emphasising the self-driving nature of the task. The automated driving task required the participant to be seated in the driver's seat and feel the speed in a given road environment. It required the participant to record their feeling of speed and feeling of risk after each automated speed scenario. By using automated driving in a given driving speed, the research can compare different road scenarios to evaluate subjective risk rating estimates and physiological responses. During the task, the experimenter was seated behind the participant to make sure the BIOPAC facility was connected and the questionnaire was presented to the participant. Speed limit credibility was investigated using a subjective measure and an objective measure in the automated driving task. Participants being a passenger feel that he/she is going too fast or too slow, feeling unsafe or very safe. The questions presented addressed credibility and risk perception (Table 3).

Table 3 Questionnaire (Task 2)

Credibility	How do you feel about the speed? Too slow ------------------------------------ Too fast
Risk	With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very unsafe -------------------------------------Very safe

During the task process, physiological measurements of EDA were recorded from electrodes placed on the fingers. The skin conductive sensors were attached to the second phalanxes of the index and middle finger of the participant's non-dominant hand, with the sensor on the bottom of the fingertips held by adhesive tape. An isotonic conductive gel (Gel 101) was applied between skin conductive sensors and the skin to improve sensors/skin contact according to traditional recommendations (Fowles et al., 1981). Thus the skin conductance response was measured by the voltage drop between the two electrodes (priya Muthusamy, 2012). The psychological measurement has been performed using the BIOPAC MP35 and the software for digital data acquisition BIOPAC Student Lab with a sampling rate of 500Hz. A laptop was used for recording data.

The driving simulator was precisely controlled in terms of timing. The trial started with a 120 seconds baseline. This period was long enough to make drivers' arousal level steady. There was an interval of 75 seconds between the start of each road scene. For each road scene presentation, the visual scene was presented with a constant automated driving speed for 15 seconds, followed by a 30s questionnaire and a 30s recovery period. An opposing vehicle passed the ego vehicle in the middle of each stimulus. During the questionnaire and recovery periods, the visual scene and motion were not activated. Each stimulus occurred in turn until all the 24 automated driving stimuli have been presented.

4 Analysis and results

4.1 Test for normality and homoscedasticity

From the questionnaire, the road layout and the roadside environment with tested speeds are independent variables; speed limit credibility chosen result, speed limit credibility rating, speed rating, risk rating and risk indicated by SCR are both dependent variables. As the speed limit credibility rating, speed rating, risk rating and risk indicated by SCR are continuous variables, numerical measures of shape skewness can be used to test for normality. Skewness is a measure of distribution symmetry (Doksum et al., 1977). For a sample of 34 participants, an estimator of the population skewness is adapted from Joanes and Gill (1998). The results show that the data distribution for each scenario is moderately skewed, which is between -0.5 and 0.5, the distribution is approximately symmetric. Thus, a parametric test was adopted. A parametric test usually has more statistical power than a non-parametric test (Finch, 2005).

The repeated measures ANOVA compares means across one or more variables that are based on repeated observations. Mauchly's Test checks for homoscedasticity (homogeneity of variances) repeated measures experiment and the null hypothesis is that all variances between all pairs of groups are equal. The Mauchly test for sphericity for each tested speed across 8 road layout reveals a p-value greater than 0.05, indicating that there is no significant difference in variances between the groups.

4.2 Task 1 Participant choice on speed limit credibility

In Task 1, the question was to choose the lowest credible speed limit for a given road shown in a picture. Table 4 shows the mode and median of the respondents' choice of speed limit. The median reflects the middle value in the list of the speed limit choice ordered from lowest to highest as the data may not be symmetrically distributed. The mode gives the value that occurred most often. Since the research is intended to identify a common choice of speed limit, the mode value was adopted as indicating the most credible speed limit. Thus, a limit of 40 mph was accepted by most respondents on four types of curved roads. For the straight roads, 50 mph was more credible on Straight + Shoulder + CycleLane and Straight + CycleLane, while 60 mph was more credible on Straight + Shoulder and Straight.

Table 4 Mode and median values for the choice of speed limit

	Mode (mph)	Median (mph)
Curve + Shoulder + Cycle Lane	40	40
Curve + Shoulder	40	40
Curve + Cycle Lane	40	40
Curve	40	40
Straight + Shoulder + Cycle Lane	50	50
Straight + Shoulder	50 and 60	50
Straight + CycleLane	50	50
Straight	60	50

4.3 Task 1 Speed limit credibility rating result

The task was to rate speed limit credibility for a given road picture with a value from very non-credible (0) to very credible (100). The higher the score, the more credible the speed limit. Respondents gave their answers via a visual analogue scale on paper. Figure 4 shows the rating scores with standard errors. Limits of 70 mph and 30 mph were seen as non-credible for any of the eight rural roads. For 60 mph, the rating was the highest on Straight + Shoulder and Straight road. Paired T-tests were used to compare the credibility scores between pairs of road layouts with the same speed limit. The 60 mph speed limit was only credible on Curve. There was no significant difference between Curve + Shoulder and Curve in terms of credibility of a 60 mph speed limit. Comparing Straight + CycleLane with Straight with 60 mph speed limit, although for both 60 mph was perceived as credible, 60 mph was more credible on Straight ($t(33) = -3.216$, $p \leqslant .05$). There was no significant difference between Straight + Shoulder and Straight in terms of the credibility of a 60 mph speed limit. 50 mph was a credible limit for all eight roads. For Curve + Shoulder + CycleLane, Curve + Shoulder, Curve, Straight + Shoulder + CycleLane, Straight + CycleLane, 50 mph was scored as most credible. A limit of 40 mph was not credible on Straight + Shoulder or Straight but was acceptable on the other six roads. However, there was no significant difference in credibility between 50 mph and 40 mph as a limit on the three curved roads — Curve + Shoulder + CycleLane, Curve + Shoulder, and Curve + CycleLane. There was no significant difference between the credibility of 60 mph and 50 mph as a limit on Curve only or for the four straight roads. Therefore, we can assume 50 mph and 40 mph were equally credible on the three curved roads and 60 mph and 50 mph were equally credible on Curve and the four straight roads.

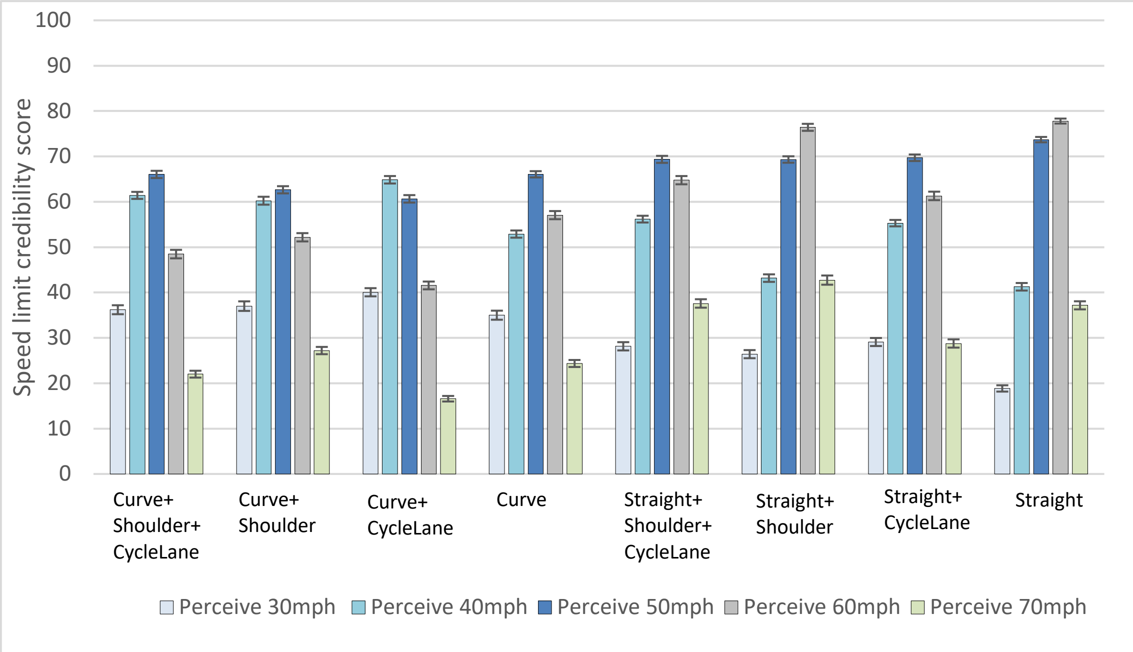

Figure 4 Credible speed limit rating score on eight roads

4.4 Task 2 Speed rating result

Task 2 was carried out in the driving simulator under the automation condition. After each 15 seconds of automated driving, the respondents were required to answer via a visual analogue scale on paper. This measurement was used to rate the sensation induced by driving at given speeds (40 mph, 50 mph and 60 mph) on eight different types of roads (Figure 5). The y-axis speed rating score varied from -50 to +50, ranging from a feeling of too slow to too fast. A score from -5 to +5 can be taken as an appropriate speed due to the allowance of error in the precision of scoring around the middle point of the visual scale.

Drivers rated 40 mph as appropriate on the four types of curved road. A repeated-measures analysis of variance (ANOVA) indicates that there was no significant difference between the four curved roads at a 40 mph automated speed (F (2.414, 79.654) = 2.873, $p > .05$, $\eta^2 = .08$). Drivers perceived 40 mph to be appropriate for all the curved roads. However, 40 mph was too slow on the straight road, so is not an appropriate speed for driving.

The drivers rated 50 mph as slightly too fast for the curved road while slightly too slow for the straight road. There was a significant difference in ratings between the four straight roads at a given 50 mph automated speed (F (2.508, 82.775) = 3.033, $p < .05$, $\eta^2 = .084$). When a cycle lane was presented on the straight road, the mean value of speed rating on Straight + Shoulder + CycleLane and Straight + CycleLane showed 50 mph to be appropriate. Drivers perceived 50 mph to be slightly too slow on Straight + Shoulder and Straight. For the straight roads, the presence of a cycle lane was used to raise drivers' awareness of cyclists and imply that they should adjust their speed to a safer level. The presence of a cycle lane on the straight road had an impact on the perception of speed, making 50 mph appropriate.

Drivers rated 60 mph to be suitable on the straight roads, but 60 mph was too fast for the curved roads. Comparing the straight roads at a given speed of 60 mph, there was no significant difference among the four (F (1.931, 63.717) = 2.045, $p > .05$, $\eta^2 = .058$). Straight and Straight + Shoulder encouraged the drivers to select higher speeds as acceptable to the road layout being simple and drivers maybe not considering cyclists too much. Both 50 mph and 60 mph driving speeds seemed appropriate for Straight + CycleLane. Whether 50 mph or 60 mph was more considered credible can be measured from other evidence.

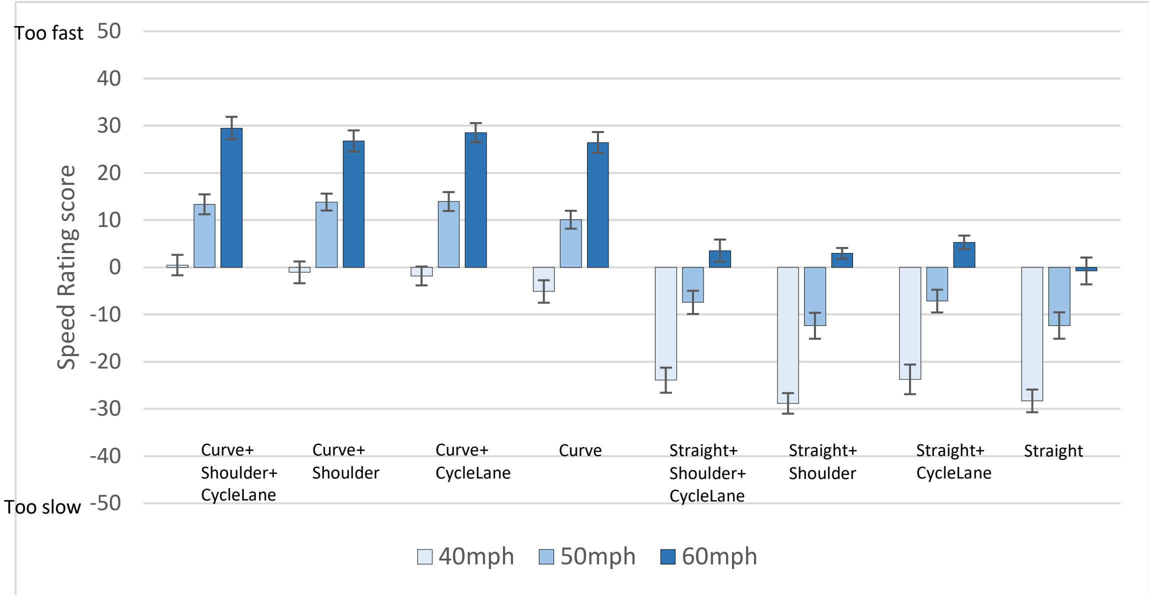

Figure 5 Task 2 speed rating result in three given speeds on eight roads

4.5 Task 2 Risk rating result

The risk ratings were conducted in the same way. After each 15-seconds of automated driving, the respondents were required to give answers via a visual analogue scale on paper. The aim was to rate the risk in terms of safety at a given speed (40 mph, 50 mph and 60 mph) on eight different types of roads (Figure 6). The risk rating score went from -50, very unsafe, to 50, very safe.

Drivers rated 40 mph as safe on all types of curved and straight roads. Straight with a cycle lane was perceived as inducing a safer feeling than the other two road types. The 50 mph speed limit provided a low sense of safe feeling on the four curved roads, thus 40 mph was preferred on curved roads. Comparison of the four curved roads at a given speed of 40 mph indicated that there was no significant difference among the four (F (3, 99) = .1.467, $p > .05$, $\eta^2 = .043$) in terms of risk rating. Drivers perceived 50 mph as safe on all the straight roads. A value exceeding 30 meant they had very safe feelings, better than at 40 mph. 50 mph provided a safer feeling on Curve + Shoulder + CycleLane than other curved roads, but there was no significant difference between the four curved roads at a given speed of 50 mph (F (3, 99) = 1.499, $p > .05$, $\eta^2 = .043$). Although 40 mph provided a safe feeling on the straight road, 40 mph could not provide a very safe feeling due to 40 mph not being credible on the straight road.

60 mph was clearly too high on the curved road, thus had an unsafe feeling. Drivers perceived 60 mph on Curve + CycleLane to have a higher risk than the other curved roads, but there was no significant difference between the four curves. Drivers perceived 60 mph to be safe on all four straight roads. The value exceeding 30 meant it provided a very safe feeling on Straight + CycleLane, Straight + Shoulder, and Straight roads. However, there was no significant difference among the four straight roads at 50 mph (F (3, 99) = .517, $p > .05$, $\eta^2 = .015$) and there was no significant difference at 60 mph (F (3, 99) = .325, $p > .05$, $\eta^2 = .010$). The

presence of a cycle lane on the straight road gave drivers a safe feeling but not approaching very safe. Compared to 60 mph, 50 mph was more suitable on Straight + CycleLane.

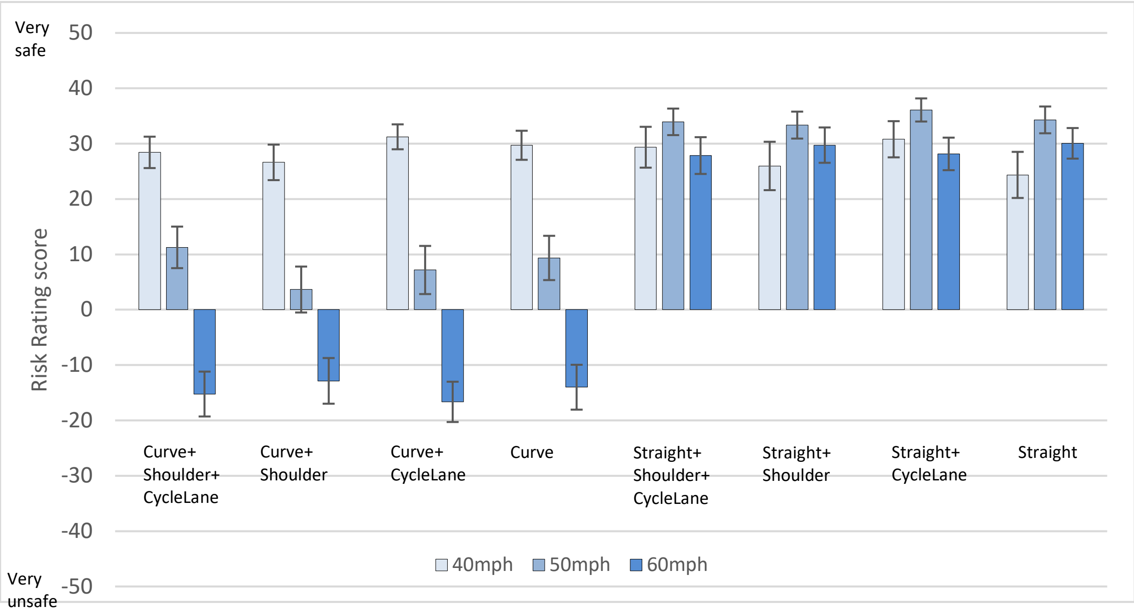

Figure 6 Task 2 Risk rating result in three given speeds on eight roads

4.6 Task 2 Risk indicated by SCR

Skin conductance response (SCR) was recorded during the Task 2 process. SCR was used to indicate individuals' arousal levels to a given stimulus, i.e. when arousal increased, SCR increased and vice versa. The results for each scenario matched with each speed are shown in Figure 7. The lowest SCR in each road scene indicated that the speed brought a lower perception of risk or more comfortable feeling which can be assumed as the credible speed limit for that situation. As an individual's electrodermal activity differs from that of others (Boucsein, 2012), the raw SCR values were transformed into a 0-1 scaling value which was used for data normalization.

Among the four curved roads, the SCR effect increased as the automated driving speed increased. The higher the driving speed, the higher the skin conductance response. There was no significant difference in SCR among the four curved roads in a given 40 mph speed (F (3, 96) = .466, $p > .05$, $\eta^2 = .014$). However, among the four straight roads, the SCR level did not increase as the speed increased.

Two conclusions can be generated from the risk response by SCR. First, the presence of curve was an important factor for drivers having lower arousal when driven at lower speed in the automated scenario. Second, the changes in SCR levels were interpreted as changes in risk perception which was only indicative for the curved roads. On straight roads, the SCR cannot generate a pattern for representing risk perception — at least not at the automated speeds used in this study.

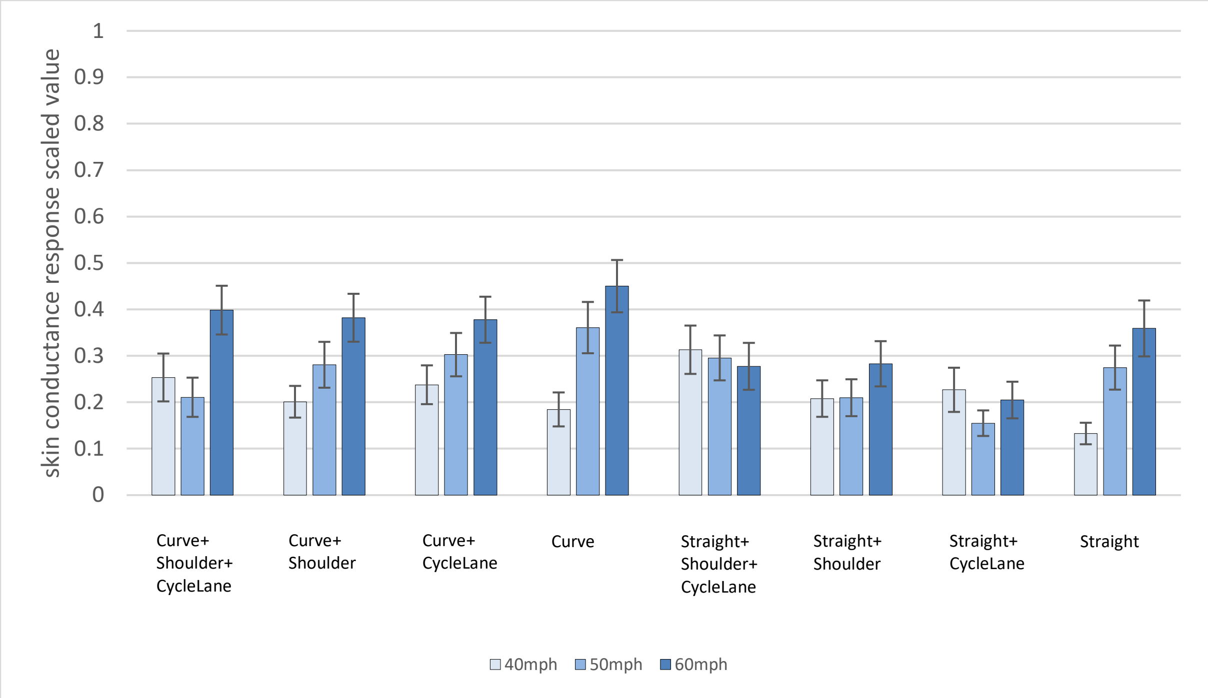

Figure 7 Task 2 Automated Driving SCR Value in three given speeds on eight roads

5 Discussion

5.1 Indicators for assessing speed limit credibility

Based on the research results, five indicators are proposed for assessing the credibility of a speed limit: the common choice of credible speed limit; the highest credible rating score value; automated speed rating as appropriate; risk rating in the range from feeling safe to very safe; and lower skin conductance arousal. That is not to say that alternative indicators are not possible. A decision on a credible speed limit needs to balance all the five factors generated from the experimental measurement results. Table 5 lists the most credible speed limit for each road type based on the five indicators for most of the respondents. If the measurements are in agreement, we can decide which speed limit would be more credible on this type of road. If the measurements contradict each other, there is a need to balance the five different aspects to decide on a more credible speed limit. As the overall criterion was that the speed limit was accepted by most of the drivers, the mode value was chosen as the basis of decision. Although the static picture and automated driving feeling could not generate the exact same conclusions on speed limit credibility, the combined indicators including single choice, credibility rating, speed rating, risk rating and electrodermal activity together can enable a reasonable and comprehensive decision.

Table 5 Speed limit credibility indicators

	Task 1 Questionnaire		Task 2 Automated driving			Credible speed limit decision (mph)
Road layout	**Credible limit chosen (mph)**	**Credibility rating (mph)**	**Speed rating (mph)**	**Risk evaluation (mph)**	**SCR arousal (mph)**	
Curve + Shoulder + Cycle Lane	40	50 and 40	40	40	50	**40**
Curve + Shoulder	40	50 and 40	40	40	40	**40**
Curve + Cycle Lane	40	40 and 50	40	40	40	**40**
Curve	40	50 and 60	40	40	40	**40**
Straight + Shoulder + Cycle Lane	50	50 and 60	50 and 60	50	60	**50**
Straight + Shoulder	50 and 60	60 and 50	60	50 and 60	40	**60**
Straight + CycleLane	50	50 and 60	50 and 60	50	50	**50**
Straight	60	60 and 50	60	50 and 60	40	**60**

SWOV (2012b) states that it is possible to determine a limit that is more credible for all drivers since they are to a large extent influenced by the same road and environment features. This research has confirmed that speed limit credibility can be determined by two factors: the road and roadside environment layout and risk perception from a person's own estimate of the hazard level. The result showed that 40 mph was more credible on four curved roads. A limit of 50 mph was more credible on Straight + Shoulder + Cycle Lane and Straight + Cycle Lane. A limit of 60 mph was more credible on Straight + Shoulder and Straight.

A curved road has a credible speed limit lower than a straight road due to the presence of potential risk. The presence of a cycle lane on the straight road resulted in a credible speed limit lower than the straight without a cycle lane. Thus, the presence of a cycle lane on the straight road was an important factor affecting credibility. Presence of a cycle lane can be seen as an infrastructural means to remind drivers that cyclists may appear on that road, but a road without cycle lane did not provide that clue and drivers may therefore not consider cyclist presence.

The experiment has confirmed that speeds perceived as too fast or too slow cannot generate a very safe feeling. Appropriate speed on the straight road can bring a very safe feeling to all the respondents but appropriate speed on curves might not still bring a very safe feeling for the respondents. That was because feelings of risk persist when driving on curved roads. These results confirmed that a speed limit is more credible when the limit in force conforms more to what the road user intuitively considers to be safe determined by a broad range of road and road environment characteristics (van Nes et al., 2007). The credible speed limit can be used for long-term planning and for demonstrating the options in producing an inherently safe system.

For the relationship between speed rating and risk rating, on the four curved roads, as the driving speed increases, the more risk is felt. All of the respondents perceived 60 mph was fast or very fast on curved roads and had a risk feeling from neutral to unsafe; 50 mph was fast for the curved road as well; 40 mph brought a sense of appropriate speed and a feeling of safety to most drivers on Curve+Shoulder and Curve. In contrast, there was a larger standard deviation with different opinions toward speed feeling on Curve+Shoulder+CycleLane and Curve+CycleLane. On the straight road, the majority of the respondents perceived it to be safe on the straight road with speed limits of 40 mph, 50 mph and 60 mph. There was a small group of respondents who perceived lower speed on a straight road as giving them an unsafe feeling, perhaps because they anticipated that this slow speed may frustrate other drivers following behind.

5.2 Research methodology validation

In terms of research methodology, the Task 1 picture questionnaire generated a significant result to distinguish the eight different road layouts in terms of credibility perception and risk perception. The lower speed limit was more credible on the curved road which met the original expectation. The Task 2 automated condition in the driving simulator, which has not been previously used by researchers, can generate valid measurements for speed feeling and risk feeling as well as useful electrodermal responses.

In terms of driving simulator physical validity, the components include: vehicle dynamics, 8 degree of freedom motion base, visual system in terms of brightness, contrast, resolution, field of view, and size of the projected world, the fidelity and elements of the sound system, and the elaborateness of the physical vehicle controls and displays with which the driver interacts. Therefore, in the controlled road environment, subjective speed perception and risk perception data can be collected using an experimental design with a repeatable and systematic process.

5.3 Study implications

This study confirms several issues which are in accordance with SWOV (2012b) research. Firstly, it is possible to choose a speed limit that is more credible for everybody. Secondly, credibility is a sliding scale from very credible to very non-credible. Thirdly, where a speed limit is not credible, the limit or the layout of the road or the environment should be changed. This research confirms the statement from ETSC (2010) that credible speed limits are expected to encourage drivers to keep to the limit. If a speed limit is not credible, there are two possibilities, either changing the limit or changing the layout of the road or surroundings. This study also confirms that various road layouts and roadside environmental factors are shown to affect speed limit credibility (Goldenbeld and van Schagen, 2007; Elliott et al., 2003; Lee et al., 2017). These factors are adopted for the research on speed limit credibility and speed choice.

Voluntary compliance is needed for speed management. To achieve that, speed limits should be credible. Otherwise once fear leads to compliance. This is also the justification of self-explaining road that drivers can easily recognise as requiring specific kinds of driving behaviour. SER aims to achieve driver self-compliance with speed limits. SER is also identifiable and leading to a significantly more uniform mean driving speed, due to the road characteristics being an important determinant of homogeneity in driving speed (Houtenbos et al., 2011).

5.4 Study limitations

The experimental design only investigated a rural single carriageway with three factors, a curve, hard shoulder and cycle lane, making eight road layout combinations in total. Other road layouts were not taken into consideration. In addition, the experiment did not involve other road users' perceptions of speed limit credibility.

Absolute correspondence between the simulator and on-road speeds is not always obtained (Godley et al., 2002). The simulator sickness is an inconvenience for the group of participants but not all types of participants are affected at an equal rate. The simulator offers the researcher of driver behaviour an advantage that real-world studies cannot match: the ability to control experimental conditions and create prescript scenarios (Carsten and Jamson, 2011). In addition, driver motivation and level of perceived risk in a simulated environment are also questionable. For example, cognitive and psychophysiological have a significant impact on the assessment of risk perception during driving (Underwood et al., 2011). As drivers practised a driving session in the simulator at the beginning of the tasks, they were familiar with the high fidelity in-vehicle surroundings and high fidelity road environment. Those limitations were minimized accordingly.

6 Conclusions

To sum up, this research has justified how credible speed limits can be set based on subjective and objective measurements by using questionnaires and driving simulator studies. Credible speed limits were here defined as the speed limits which are accepted by most of the drivers without the need for enforcement in a given road layout. A valid methodology, which can be adopted for further investigation, has been developed to evaluate credibility. Setting credible speed limits is strongly based on road design. Curved roads and roads with cycle lane need lower speed limits because of the potential risks presented. Adding a cycle lane and a warning sign on a straight rural road is suggested to make a 50 mph speed limit more credible. It is not suggested to have 60 mph on roads with a cycle lane and or on curved roads with a 200m radius. In addition, setting speed limits that are credible will help bring about greater compliance. Setting speed limits that are credible has an important role in speed management, since doing so reduces the need to devote resources to enforcement and campaigning in the endeavour to achieve compliance.

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